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technical note

Air Traffic Controller Scanning and Eye Movements in Search of Information - A Literature Review

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March 1989

DOT/FAA/CT-TN89/9

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U.S. Department of Transportation
Federal Aviation Administration

Technical Center
Atlantic City International Airport, N.J. 08405

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/CT-TN89/9		

4. Title and Subtitle	5. Report Date
Air Traffic Controller Scanning and Eye Movements in Search of Information - A Literature Review	March 1989
	6. Performing Organization Code: ACD-340
7. Author(s): Earl S. Stein, Ph.D	8. Performing Organization Report No.: DOT/FAA/CT-TN89/9
9. Performing Organization Name and Address: Federal Aviation Administration Technical Center Atlantic City International Airport, N.J. 08405	10. Work Unit No. (TRAIS) 11. Contract or Grant No.: F2003D
12. Sponsoring Agency Name and Address: Federal Aviation Administration Federal Air Surgeon 800 Independence Avenue S.W. Washington, D.C. 20591	13. Type of Report and Period Covered: Technical Note June-December 1988 14. Sponsoring Agency Code: AAM-1

15. Supplementary Notes

16. Abstract

The Federal Aviation Administration is engaged in an on-going research effort designed to help air traffic controllers reduce the frequency of operational errors. This literature search and review was a first step in the study of controller scanning for information. Results indicate that the study of eye movement is a very complex process even given the current technology available. Another finding is that there has been very little accomplished in the study of air traffic controllers scanning and eye movements. The field is wide open and the potential benefits are large. Keywords:

17. Key Words	18. Distribution Statement
Air Traffic Control, Human Factors Eye Movement Scanning.	This document is available to the U.S. public through the National Technical Information Service, Springfield, Va. 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	30	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Continuing research on errors committed by air traffic controllers has indicated that they frequently report a failure to see critical information on their displays. There are many possible reasons why an operator will fail to take in and process necessary information, resulting in a decision which can potentially lead to serious problems. There has been very limited research on why controlers might fail to take in critical information. In April 1987 a Federal Aviation Administration (FAA) Administrator's task force on operational errors identified two major areas for additional emphasis: controller memory enhancement and information scanning. This focus was passed by the Air Traffic Service to the Federal Air Surgeon, who, in December 1987, requested support from the FAA Technical Center. A program directive was initiated in April 1988.

This literature search was accomplished as the first component of what is hoped will be an ongoing study of how controllers search for and employ the large volume of visual information they must constantly use. Over a 5-month period, an in-depth search was made using multiple automated data bases. At the center of this search were any and all reports, papers, and other published works which related to human eye movements involving complex person-machine relationships in applied operational settings. Once references were acquired they had to be ordered, received, read, and categorized. This occurred while other documents were in transit and was an ongoing process even into the writing of this Technical Note.

The results of this search and analysis are presented in this document. This includes a short course on the nature of eye movements to help the reader follow the terminology and a review of measurement methods. The Technical Note covers work done in non-aviation related vigilance studies, which are relevant because of the person machine interface questions addressed. It covers the limited literature generated from cockpit studies and the very limited products which have been developed in air traffic control (ATC).

Findings of the literature review confirm what was suspected. There has been precious little accomplished in the effort to quantify how controllers acquire information. The systematic measurement of human eye movements is a difficult process, even given state of the art technology which tends to be less than user friendly.

Technology available involves tradeoffs between cost, accuracy, and intrusiveness on the operator. The variables of primary interest have been: point of gaze or line of sight, fixation frequency and duration, and the speed and length of saccades - which is the principle short movement that the eye makes when jumping from one point to the next (three to five times per second).

This is a very potentially fruitful area for research which could pay huge dividends on the investment as more is learned about how controllers acquire information. The degree to which this knowledge gap is closed will depend on the availability of personnel and other resources. The FAA Technical Center already owns a sophisticated state-of-the-art oculometer which will be the central focus of the empirical efforts in this ground-breaking program.

INTRODUCTION

CONCEPT

There is an old dictum often voiced by those who claim to be in the know: "Seeing is believing." In the reality defined by experience, people often grasp at simplistic explanations without fully understanding what they are saying. In the world of human perception, vision is generally accepted as the dominant means of gathering information. It is, however, infinitely more complex than many are willing to believe. Yet people, highly trained and competent professionals, make mistakes. They make judgments based on the belief that they have absorbed all there is to see, and, in fact, there was data available right in front of them that they did not see. There is no dictum that quite covers this. If there was, it might read: "If you don't look at it, you can't see it."

No supervisor, leader, or researcher can judge what another human being sees or does not see. They can only infer based on what the individual says that he sees and what he subsequently does about it. In a highly complex person-machine system like ATC, defining and avoiding human error is a major concern. One of the most frequent statements made by personnel who have made a mistake is: "I didn't see it." In an effort to understand why and subsequently to reduce human errors in air traffic control (ATC), the Federal Aviation Administration (FAA) in 1988 initiated a program in Controller Information Scanning.

PROGRAM BACKGROUND.

The ATC System has evolved over the years in response to user needs and available technology. Historically, the ATC process has been very human centered and dependent on the ability of air traffic controllers (Thomas, 1985). A great deal of what controllers do involves information acquisition and processing (Kirchner and Laurig, 1971; Sperundio, 1971). Everyone has limits in terms of the amount of information they can reasonably handle (Finkelman and Kirchner, 1980). With the technology of the 1980's, controllers must attend to a wide range of detail. The future holds out the hope of machine assistance for the management of information. It remains unclear what the impact will be on human operators (Jenny and Ratner, 1974). Controller acquisition of knowledge and how it will be used are complex questions which bear further study (Spettell and Liebert, 1986; Warm and Dember, 1986).

Regardless of when or what promises technology holds for the future, the FAA still must deal with the present and the everyday potential for human error. In April 1987, an FAA Administrator's task force on ATC operational errors identified a number of factors that contributed to the nature and frequency of

controller errors. Two areas in particular were highlighted by an operational error analysis work group. These were controller memory lapses and controller information scanning.

A meeting was convened in June 1987 by Air Traffic Requirements (ATR) to discuss the nature of scanning and its impact on operations and training. It was noted that while automation had increased the number of aircraft that a single controller could work, controllers continued to make the same sort of mistakes, and these were often attributed to a failure to perceive critical information. During this meeting, it became apparent that despite the ease with which people used the concept of "scanning" and the fact that whatever it was, it "has been done forever," no one had ever really defined scanning in an ATC context. The following definition was suggested by an FAA Technical Center psychologist and, after some editing, was accepted by the group. It is presented below in its edited form:

"Scanning is a systematic and continuous effort to acquire all necessary information in order to maintain complete awareness of activities and situations which may affect the controller's area of responsibility."

Prior to the development of this definition, there were several initiatives by Administrators in Air Traffic and Aviation Standards. In December 1987 these efforts led to the Office of Aviation Medicine and the Federal Air Surgeon to request the beginning of programs in controller memory and scanning.

This literature review became the first element in the Scanning Program. Technical Center psychologists suggested that the key to unlock the mysteries of scanning might be the evaluation of controller eye movements. There was some equipment already available to accomplish this task. The purpose of the literature review is to identify the nature of the variables that have been employed in eye movement research and to determine methods and applications of eye movement technology. Of particular interest were those applications related to aviation and ATC. What will become apparent is that while there is some literature on controller eye movements, it is very limited; and, in fact, this is a virtually unexplored area which may well serve as a window into air traffic controller information processing.

A SHORT COURSE ON EYE MOVEMENTS

"Man reveals many of his secrets in the pattern of his eye movements, a fact appreciated by oriental merchants, poets and policemen at least as long as it was by psychologists" (Alpern, 1971, p 369). Our ability to discriminate detail, often referred to as our visual acuity, drops off rapidly as light impinges further away from the eyes' point of clearest vision - the fovea. The eyes are practically in constant motion driven by

six muscle groups which are among the fastest in the human body. We have the illusion of a stable visual field despite the constant eye movements and despite the fact that when the eyes are moving they are not taking in any information. Our impression of spatial solidity is created by our central nervous system, and the movement of the eye muscles is coordinated by a switching circuit in the brain stem. Actually, our eyes are not in constant motion. If that were true, we would be unlikely to see anything at all. Saccadic movement only occupies about 10 percent of the total viewing time (Norton and Stark, 1971). The majority of time during our waking hours the eyes are stopped or fixated on objects and events in the surroundings. This is when they are acquiring information to reduce our level of uncertainty.

There are two general classifications of eye movements: Version, which includes saccadic and pursuit movements, and Vergence, which involves convergence and divergence. Version implies that the individual is viewing information at the same relative distance from his/her eyes as would be true when monitoring a radar display, for example. The saccadic movements are what we usually see when watching another's eyes. These are the sudden parallel changes in the fixation point of both eyes. They are very rapid and may well occur three to six times per second. In 100 milliseconds or 1/10 of a second the eyes can shift as much as 40 degrees (Alpern, 1971). Pursuit movements occur when the eyes are tracking a moving target. This includes saccadic movement plus smoother pursuit movements. The purpose of pursuit activity is to maintain the tracked image stationary on the visual sensory organs in the retina of the eye. Unlike Version, Vergence eye movements involve a change in the intersection of the lines of sight of the two eyes. This occurs when the distance changes as it might if a radar operator turns from his display and focuses on another source of information, such as the face of an adjacent operator. Convergence occurs when the new distance is closer; divergence happens when the distance increases. Frequent changes of vergence in the operation of a system has been identified as a source of visual fatigue.

In applied settings, the angular distance between old and new fixations is often covered, in part, by head movement and partly by the eyes. The central nervous system takes head movement into account. As will be seen later in this monograph, head movement which is a natural component of search behavior, presents a significant problem for the technology of eye movement measurement (White and Ford, 1960).

Again, in the everyday world or a realistic simulation of it, vision involves both Version and Vergence. Saccadic movement is 20 times faster than Vergence. If distance changes are involved, at the completion of each saccade only about 6.5 percent of the Version, adjusting to the new distance, is completed.

There is a diversity of opinion concerning the role of eye movements in larger scheme of things relative to system operation and performance. Human beings rarely, if ever, function based on one discrete aspect of their perceptual capabilities. Johnson, Howell, and Williges (1969), writing about what they viewed as the components of complex monitoring, stated that performance had to involve both scanning and memory. The individual must scan for information and compare input with remembered states. The faster he scans, the shorter will be the time delay (detection latency) in identifying critical information. Patterns of visual scanning may include biases which lead to inconsistent performance and, in many cases, no one knows what is the optimum scan pattern (Wallis and Samuel, 1961). Many of the lab studies investigating human behavior during monitoring type tasks are only dealing with performance in relatively alert operators who have reason to expect that "critical" information will be present. The nature of the eye movements acquired in such a situation may not be good predictors of what people will do under task load. There are very few situations in the "real world" where apriori assumptions are made concerning optimal scan patterns. Pilots are one group of operators who are actively taught to scan instruments and airspace in a systematic and continuous pattern. The spatia-temporal pattern of their eye movements can comprise what one group of authors called "the good scan." (Tole, Stephans, Vivaudou, Harris, Ephrath, 1982).

Currently there does not seem to be any concept of "the good scan" in ATC. Examining the possibilities and trying to identify the elements of effective scanning requires more than analysis; it requires systematic measurement. As the next section will show, there are many ways to measure and evaluate human eye movements.

METHODS OF MEASUREMENT

The alternatives for measuring, recording and compiling human eye movement in the 1980's are limited primarily by the investigators' budget, time available, and technological sophistication. Eye movement recording always involves a series of tradeoffs, even given unlimited funds, which is a luxury few researchers ever experience. Other variables in a tradeoff equation involve the amount of accuracy desired (often measured in degrees, minutes, or arc seconds), and the level of intrusion that is acceptable (table 1). For example, there is one system that is called the "optical lever." It involves a precision ground contact lens with mirrors ground into its surface which reflect light onto a detector, such as film or a TV camera. This system is noteworthy because it is accurate to a tolerance of 5 arc seconds. It is also noteworthy because it is very expensive and presents a physiological risk to the wearer. Common contact

TABLE 1. MEASUREMENT METHOD MATRIX

Method → / Parameter	Contact Lens	Direct Observation	Electro Occulography	Photography	Head Mounted Photo Sensors	Corneal Reflection	Occulometer
Angular Field of View (Degrees)	$\pm 10^{\circ}$	No Limit	$\pm 50^{\circ}$	Equipment Dependent	$\pm 20^{\circ}$ Horiz. $\pm 10^{\circ}$ Vert.	Equipment Dependent	$\pm$ 20-40° Depending on Equipment
Cost	High	Low	Moderate	Low-High	Moderate	Moderate-High	High
Obtrusive to Participant	Very High	Low-Moderate	Moderate	Moderate-High	Moderate	Moderate-High	High
Angular Sensitivity (Degrees)	$\pm 0.0001^{\circ}$	Observer Dependent	$\pm 2^{\circ}$	Dependent on Film Resolution and Magnification	$\pm 0.25^{\circ}$ Horiz $\pm 1.0^{\circ}$ Vert	$\pm 2^{\circ}$	$\pm 1^{\circ}$

lens move somewhat on the surface of the eye. The optical lever is ground to fit so tightly that it may deform the surface of the eye and damage the muscles which allow for accommodation to distances (Young and Sheena, 1975). Such a system is highly accurate, but is limited to movement ranges of about 5 degrees and there may be severe limitations in obtaining voluntary participants.

Eye movement recording requirements have challenged the ingenuity of researchers as well as rug merchants. The range of technology is very broad. David (1985) reminds his readers of the simplest, no-tech method ever devised. This is direct observation by researchers who are looking for specific behavior within a limited domain. In an experiment on the measurement of air traffic controllers eye movements, David (1985) had observers tallying the frequency and duration of glances at an electronic data display. The major advantages of the method include its flexibility and to quote the author "It is cheap." Disadvantages are that it is observer intensive, depends on observer attention, motivation, and reaction time, and observers tend to miss a proportion of brief glances. Other disadvantages not cited by the author include its crudeness and lack of precision. Further, direct observation may have a social psychological impact on the operator; it can be intrusive. However, according to Alpern (1971) in his survey of methods, the analysis of eye movements has been a time honored pursuit of psychologists since the early part of the 20th century, and an experienced watcher could detect movements as small as 1/2 degree. It may well be easier to buy equipment than it is to find that experienced watcher.

The most comprehensive summary of eye movement recording methods to date was accomplished by Young and Sheena (1975). All eye monitoring approaches fall into two categories: the measurement of the position of the eye relative to the head, and the measurement of the orientation of the eye in external space. Techniques included in the first category are the contact lens method of which the optical lever is one example, electro-oculography, and a number of photographic methods which focus exclusively on the head and eyes. The second category has been referred to as point of regard or point of gaze measurement. This includes photographic methods and oculometric methods depending on reflected light from various components of the human eye. There is also a group of methods which include head position sensors for the purpose of separating head movement from eye movement, which is a major problem in many of these systems, often solved by restrictive techniques limiting the head's motion. Methods which have not already been described are discussed below.

Electrooculography is a technique which has been around for many years and is still in active use today, in some cases because of its ready availability to investigators. It involves the recording of electrical potential changes around the eye using

attached electrodes. There is an electrostatic field which rotates with respect to the eye. While this system can be used for recording eye movements up to 50-70 degrees, the linearity of the system begins to breakdown at about 30 degrees from the initial fixation point. The system requires a lot of time to set up and calibrate, and there is problem with direct current drift requiring recalibration. Estimates of point of gaze can be made by starting from a known fixation point and measuring angular displacement. Estimates of accuracy with a good operator are plus/minus 2 degrees as compared to the contact lens method of plus/minus .01 degree. Electrooculography involves connecting a participant to a machine with wires dangling from his face and very limited head movement restricted by a head rest or bite board. It is less than comfortable. The results can include the frequency and duration of fixations, and the length of saccadic jumps.

There is an entire group of techniques which involve photographic or video tape recording of eye movements. This class of technology includes head mounted cameras, which are physically very intrusive, and remote photography, which is both less bothersome and less expensive. All photographic techniques are dependent on film resolution and optical magnification and involve very restricted head movement (Davis, Lutz, Warner, and Iannini, 1971). A major problem with photo methods is translating the video information into a form that is experimentally meaningful. This could mean manual transcription, a very labor intensive operation (David, 1985). Whenever you have manual coding of data, there is an increased opportunity for human error during the transcription process. An additional problem in the remote photography of eye movements is camera placement within the work station. The applied situation may dictate available space, and changes to the work station may have an impact on the results.

Another class of recording methods for eye movements relative to the head employs head-mounted photo sensors. Norton and Stark (1971) reported a laboratory study using photocells attached to eye glass frames and wired through amplifiers to an oscilloscope and a tape recorder. The photocells determined the movements of the "white" of the eye, which were then recorded on magnetic tape and could later be played back at a slower speed. The accuracy of this recording system varies differentially for horizontal and vertical eye movements, respectively (plus/minus .25 degree horizontal and plus/minus 1 degree vertical).

This is certainly not prohibitive, but data analysis (at least in 1971) still involved manual transcription and coding. The authors indicated they were working on a automated system, but there was no evidence whether or not this was ever accomplished. The sensors on the eye glass frames did provide more flexible head movement. Each researcher would have to determine how much

lateral head movement could be accepted and still have meaningful results without point of gaze recording.

Another system which depended upon reflected light was described by Young and Shenna (1975) as the Corneal Reflection Method. Light is reflected from the convex surface of the eye (cornea) and is picked up through a concave lens. The light is then recorded on a film plate, TV camera, or photocells. Early systems using this technology required that the head be locked in place by a clamp or bite board. Any lateral movement relative to the light source or recording devices would induce large recording errors. A latter adaptation of this system employed a head mounted corneal reflex camera which recorded the scene observed with the fixation point superimposed. The accuracy was lower (plus/minus 2 degrees) than with the fixed head system. The weight of the head mounted equipment was significant and intrusive.

So far the methods described have been primarily those that examine eye movements in an environmental vacuum. The researcher knows what participants are scanning, but he/she can often only estimate where they are looking. Eye movements relative to the head are important for evaluation of the nature of eye movements. In most applied settings, however, the purpose of the research is to better understand how people are gathering information from stimuli and displays available. The need for this sort of data stimulated the evolution of new technology geared towards the assessment of line of sight, point of gaze, and eye movements relative not only to the head, but to the outside world (within the limits set by the laboratory).

One way to obtain point of gaze information is to photograph the eye's surface with a very high resolution camera and actually record the scene reflected by the cornea at the center of the pupil. A device which does this is a polymeric wide angle eye movement recorder. It generates a photograph from which fixation points can be determined. Its maximum sampling rate of 12 frames per second is relatively slow.

In the mid 1960's, eye movement measurement graduated to a higher level of technology with the evolution of a series of oculometers. Many of these devices, while varying in capability and complexity, were based on a few principle optical concepts and generally involved computers for both operation and data collection. One of the best descriptions of this technology was written by two researchers at the United States Army Aberdeen Proving Ground in Maryland. Mazurlzak and Pillalamarri (1985) wrote about the Human Engineering Laboratories' effort to develop unobtrusive methods for the evaluation of equipment operators eye movements. They noted that the use of constraints in any measurement system makes the generalizability of the results questionable. The more obtrusive the instrument, the greater is the probability of obtaining distorted measures. The oculometer

at the Human Engineering Laboratory is based on the collection of reflected light from the eye. The system employs an infrared (IR) light source with an optical head or mirror which collects the light reflected from the eye. A participant's eye movement with respect to the head and, subsequently, with respect to the point of fixation, is computed by the measurement of the center of the pupil with respect to the center of the corneal reflection. When the entire head moves, the center of the pupil and the center of corneal reflection move together. When the eyes move in the head, the relationship of the pupil and the corneal reflection changes proportionally based on the degree of eye movement.

Once the system is set up and the participant is in place, the operator of the oculometer manually acquires the center of pupil by adjusting a joy stick controller while viewing the participant's eye on a TV screen. The operator enters values which set thresholds for the pupil discriminator and the corneal reflection discriminator so that the detections by the computer algorithms are reliable. The optics or optical head driven by the computer tracks the participants eyes, and the system allows limited head movement as long as the eye image remains centered in the field of view. The system is coupled with video cameras and monitors so that the operator can view the participants eyes along with the point of gaze superimposed as cross hairs on a video image of the screen.

The Human Engineering Laboratory oculometer is quite typical of this level of eye measurement instruments. It records pupil diameter and works best when the pupil exceeds 3 millimeters. Its accuracy is approximately plus/minus 1 degree. It allows about 1 cubic foot of head movement. If the participant exceeds that, then pupil acquisition is lost and has to be manually reacquired. Loss of tracking can also occur by prolonged eye blink, coughing, sneezing, or anything which might mask the pupil or corneal reflection. The system collects calibrated X and Y coordinates of fixation points on the stimulus scene at a sampling rate of 60 per second. The sampling rate is limited by the scan rate of the TV equipment. While this system is not perfect, it does allow more flexibility and less obtrusiveness than those methods requiring complete head restrictions. It will collect fixation position and duration and overlay them on the visual scene. The system can handle a great deal of digital data with minimal manual input.

Some of the head movement restrictions can be further lessened in applications such as aircraft cockpit research. Young and Sheena (1975) described a group of methods which basically involve more accurate assessment of head movement so that it can be separated from eye movement. These methods involve wearing a helmet or device which contains either sensors or transmitters. Optical head position sensors can measure the X Y position of a small point attached to the head or an array of light sources on a

helmet. A system developed for tracking a pilot's line of sight used photo detectors on a helmet and IR light sources in the cockpit. Another approach had ultrasonic transmitters in the cockpit, detectors on the helmet, and computed head position based on ultrasonic delay time. One of the more cumbersome ideas included a helmet attached to a mechanical array and, subsequently, to transducers. There have been few limits to the ingenuity of researchers, and each method has its strengths and weaknesses. As indicated earlier, there are always tradeoffs. One of the most important tradeoffs is between participant comfort and safety versus accuracy and precision. Another tradeoff is between range and accuracy. Some methods allow a wider range of measurement, i.e., 50 to 70 degrees of eye movement, but tend to be less accurate and suffer more lost data. Finally, every researcher has to deal with cost. Research goals determine, in part, the minimal equipage. The more information accurately recorded, the more expensive the method will be. Determining point of gaze generally costs more than evaluating saccadic eye movements with respect to the head alone.

To this point, the nature of eye movements and the methods used to measure them have been reviewed. The section which follows will briefly examine an area of human research which has been a major source of concern in applied settings and which has touched on the technology of eye movement measurement. This area is "vigilance."

VIGILANCE STUDIES AND EYE MOVEMENTS

The fact that vigilance is even mentioned here in a monograph on eye movements is a function of the fact that much of the great volume of vigilance research has a good deal in common with the primary ATC focus of this work. The concept of vigilance appears to mean different things to different people. At its most basic level, it implies the gathering of information over time by human operators who monitor one or more display channels. Vigilance research suggests that this process is less than perfect and that there will be an error rate induced based on a tremendous variety of variables which focus on the nature and method of displays coupled with the duration of the monitoring task and the characteristics of the operator.

According to Adams (1987), vigilance research has been popular for over 40 years, and much of it has emphasized performance decrement over time. According to Mackie (1987), over 1000 studies have been published. Much of this work has been accomplished in laboratories, and very few real world performance decrements have been identified. Many of the tasks have been artificial and simply did not generalize to an operational environment. Despite the fact that vision is generally accepted as the dominant perceptual system, and that much of monitoring is

much of monitoring is visual, surprisingly little has been done in vigilance research regarding the nature of eye movements.

A study which acknowledged the importance of scanning for information without actually measuring eye movements was published by Johnson, Howell, and Williges (1969). These authors discriminated between simple and complex monitoring behavior. The simple monitoring involved relatively static and homogeneous displays with low information content. Complex monitoring occurred when information was dynamic, heterogeneous, and involved operator decision making. The authors made a series of assumptions concerning scanning. They indicated, quite logically, that if the information needed was not available at first glance, or more technically within the first fixation point, the operator would have to look for it. They also assumed that the higher a person's scan rate, the shorter would be his detection latency for critical targets. Operators have to separate relevant (R) from irrelevant (I) stimuli. There is always a ratio of R/I. As R/I increases the observer or operator should have a higher rate of correct detections, reasoned Johnson and his colleagues.

Using a laboratory detection task and a 100-minute monitoring period, the researchers experimented with two ratios: 1/9 and 9/1. They found that performance in terms of detection probabilities for valid targets was about the same. However, for the 9/1 ratio the false alarm rate (I see it but it isn't there) was much higher. The authors assumed that since the probabilities of correct detection were the same for the 1/9 and 9/1 ratios, that in the latter condition people simply scanned faster. This is a classic example where a project could have been directly enhanced beyond assumption by objective oculometery.

In contrast to vigilance studies where eye movements were not considered and to those where scanning was assumed, Dr. Richard Thackray and his colleagues at the FAA Civil Aeronautical Medical Institute (CAMMI) have conducted a series of research projects relating vigilance and eye movements. Thackray, Baily, Powel, and Toutchstone (1979) wrote about the effect of increasing the load of a human monitor on vigilance performance using simulated radar displays. The authors expressed concern about anticipated automation in ATC and how controllers would be expected to intervene based on the detection of problems. They noted that typical vigilance tasks were very simplistic and would never be able to demonstrate how well radar controllers could maintain attention using advanced displays.

Paid volunteers were assigned to one of three target density groups of 4, 8, or 16 simulated radar targets with alphanumeric data blocks. Participants were told to beware of changing data and to signal if the altitude went to "999." A number of

physiological variables were recorded including Electrooculography(EOG) of eye movements.

Electrodes were attached directly above and below the right eye. Results indicated that detection latencies increased with target densities. Eye movement information was recorded on a dynograph chart recorder. The researchers had to manually evaluate it. They searched for eye closures between target onset and detections. With limited data, they found that the frequency of such closures increased with time on watch over the 2-hour task session. However, given their methods and system noise, little else was discovered.

Thackray and Toutchstone (1981) investigated age related differences in complex monitoring performance. They noted that the results of previous work on the impact of age on vigilance performance was, to say the least, equivocal. The investigators asked paid volunteers of various ages to monitor a simulated radar display looking for changes in alphanumerics. It was hypothesized that detection latencies would increase with age. Horizontal eye movements were recorded using electroculographic equipment and electrodes. Key eye movement data were the mean fixation durations for 30 seconds prior to each correct detection and response or prior to timeout of each missed stimulus (change in altitude portion of the targets data block).

Results indicated some age related trend in response latencies, but it was not exactly linear and did not appear at all until they reached the second 30-minute block of the 2-hour task period. This was in detection latency. Errors in detection did increase significantly with age. There was no age related differences of significance in mean fixation durations. However, the frequency and duration of fixations does not provide information on the adequacy of search patterns nor does it provide much insight on search strategy.

Thackray and Touchstone (1988) examined the impact of high visual task load on complex monitoring behavior. They noted that modern command and control systems involved more than simple target detection. They require rather complex multidimensional discriminations. These discriminations are followed by an interpretation of significance and decision making. The authors decided to create a more realistic ATC simulation modeling on an intermediate level of automation involving computerized controller aides.

Departing from their past use of EOG, the researchers chose another eye movement assessment method. They employed video taping of eye movements and facial orientation in order to evaluate operator behavior when missed events occurred (participants failed to identify critical display changes). A miniature Sony camera was mounted in the lower left corner of the display console at a 45 degree angle to the participant's face.

A second camera monitored the simulated radar display. The products of the two cameras were combined and displayed on a video monitor. The monitor also recorded an indicator light (not visible to participants) which identified the occurrence of each critical stimulus.

While the video approach was a departure from EOG and chart recorders, it still required manual analysis. The investigators reported problems with both the video recording equipment and the participants' seating position. They could not always analyze facial orientation. Out of 98 missed events in the sample, only 40 had complete "visual activity" data. These data were categorized as: eyes open, eyes closed, and eyes diverted from the screen. Ninety-seven percent of the missed events occurred when participants had their eyes open and they were actively scanning the screen.

Vigilance studies have become progressively more controversial over time. Questions about realism and generalizability have challenged the worth of many vigilance projects. The work by Thackray and his colleagues provide a logical bridge from basic vigilance work and studies which involve eye movements related to aviation concerns to include display monitoring. The next section of this monograph reviews what, for lack of a better term, are practical applications of eye movement technology in complex person-machine environments.

APPLICATIONS

There has been considerable interest in display monitoring since the 1940's. However, eye movement technology did not really evolve until the 1950's. This applications section will provide a brief sampling of work in three categories: (1) monitoring and eye movements in non-aviation contexts, (2) eye movements in the cockpit, and (3) eye movements and ATC.

OUTSIDE AVIATION.

Ford, White, and Lichenstein (1959) were concerned with the eye movements of operators doing free search monitoring tasks. This has some similarity to radar operation in that participants were looking for critical information on a Cathode Ray (CRT) display. Eye movements were recorded using electrooculography which displayed changes on an oscilloscope. The authors used time delay photography of the oscilloscope to provide a time track plot of the eye movements. This provided the number of fixations per unit time and their duration. From the photo plots, the investigators could manually determine the order of fixations during search behavior and the length of saccadic jumps. The results were informative. Most participants began with rather random search patterns, but gradually these took on form,

reflecting some strategy. Participants spent 85 percent of their time fixated and 15 percent moving between fixations. The authors suggested that the less movement, the less likely was target detection. Both the center and outer rim of the display area were relatively neglected by most observers. Ford and his colleagues inferred that this could have training implications for those involved in visual search activity.

Beatty (1977) focused on an entirely different aspect of visual behavior--pupil dilation during the scanning of numerical visual displays. He had paid volunteers reading data and feeding back what they read to the experimenter. Displays were varied in terms of background noise and target quality. Results indicated that the more noise and the greater the degree of stimulus degradation, the greater were participants pupil dilations. Error rates increased significantly as display quality decreased. One interesting note on Beatty's report is that he apparently forgot to describe how he went about measuring pupil dilations. He only indicated that pupilometric measurements were made every 25 milliseconds.

In another non-aviation related study which has implications for ATC information processing, Swanston and Walley (1984) examined factors which might influence how fast an operator can read tabulated data. The investigators were concerned with viewing distance and the physical separation between points on a display. They employed a state-of-the-art Gulf and Western eye tracking system and asked participants to search from a fixation point to a target (a three digit number) displayed on a CRT. Response latency was measured with a voice key when the participant read the three digit number. As hypothesized, latencies increased as the distance between initial fixation and target increased. This was determined without the oculometer. What eye movement measurement confirmed was that longer latencies were not a function of reverse eye movements, a characteristic of the inexperienced such as when learning how to read. When eye movement data were compared to response latencies, it was determined that a good portion of the response latencies were not accounted for by eye movements. The eyes were already on the target for awhile before the individuals responded. Swanston and Walley (1984) speculated that this may have involved a need by the participants to analyze and encode the verbal information after they fixated on the target. This apparently takes longer with larger displacements of fixation. These results imply that tabulated data should not be any further than absolutely necessary from primary displays.

Leermakers and Boschman (1984) used another sophisticated oculometer, an SRI Dual Purkinje image eye tracker, to evaluate "visual comfort" as a function of eye movements. Participants examined CRT displayed text material made up of random strings of 36 characters per line and 16 lines in length. They were asked to search and count the frequency of "A's" in the text. Upon

completion, they rated their visual comfort from 1 (extremely poor) to 10 (excellent). Fixation durations and length of forward saccades were not related to the luminance of stimuli, but did correlate with visual comfort ($r = -.87$ fixation duration and $r = .85$ with length of forward saccades). The fixation durations were longer and the forward saccades were shorter than when reading normal text. During the most comfortable conditions they were 320-340 milliseconds (msec) as compared to 200-260 msec for conventional reading. The results demonstrated that participants could reliably rate their visual comfort as a means of evaluating visual displays. Also, more precise understanding of how information is actually extracted requires eye movement data.

The applications studies cited to this point provide insight into the use of eye movement measurement and do have some implications for aviation. Now the focus will shift to work accomplished specifically to better understand aircrew and air traffic controller behavior.

AIRCREW.

Eye movement techniques have been used much more extensively in cockpit research that in ATC environments. The cockpit is a more restrictive environment and pilots engage in less physical movement relative to their displays than do controllers. This makes it considerably easier to adapt the measurement technology. Despite this, Morris (1985) indicated that little work had been done to relate electrooculographic measures to flying performance. What he may have left unstated is the intrusiveness of EOG electrodes on a pilot's face. Morris hypothesized that a number of visual parameters (eye blink rate, duration of blink, long closure rates, saccade velocities) would be correlated with pilot performance decrements associated with fatigue. Ten pilots flew a General Aviation Trainer (GAT) flight simulator, and eye movements were collected using electrodes connected to a polygraph and a PDP 11 computer. Pilots flew a 4-1/2 hour mission after being awake the previous night. While no single eye movement variable accounted for more than 41 percent of the errors committed by pilots, results indicated a number of relevant correlations: blink duration $r = .496$, blink amplitude $r = -.599$, saccade rate $r = -.492$. The more eye movements the less errors committed by the tired pilots. Saccade rate is synonymous while scanning.

Many applied cockpit scanning studies have been accomplished by the National Aeronautics and Space Administration (NASA). These studies have attempted to evaluate the impact of new procedures, equipment, and instruments. They demonstrate very practical applications of eye movement methods.

Spady and Harris (1981) described research on the use of altimeters and indicated that pilot errors in reading these instruments have resulted in many accidents. They mounted an oculometer in a Boeing 737 simulator to monitor pilot look points on the instrument panel along with pupil diameter. The project employed airline pilots who did traditional landing approaches. Past experience has indicated that pilots will tell you that they spend 20 percent of their scan time or dwell on the altimeter during approaches. This study documented that only 3 to 6 percent of total scan time was actually spent on the altimeter.

Harris and Mixon (1981) were concerned with pilot scanning behavior during the new curved landing approaches made possible with microwave landing systems. They wondered whether information search strategy would change in comparison to that used in conventional instrument landing approaches. Using a fixed-base flight simulator equipped with an Electronic Altitude Display Indicator (EADI), which presented a planned ground track in a map format, they monitored pilots eye movements using a commercial oculometer. The electro optical head and camera were mounted on the glare shield of the simulator.

Eye data collected included: Dwell percentages, Dwell times, transition percentages, look points, and pupil diameter. Only three test pilots participated. Dwell percentages were computed based of the amount of time the pilot looked at a particular display divided by the total time the oculometer was tracking the pilot. Dwell time referred to the total time the pilot spent looking at a given display divided by the number of times he looked at it.

The system sampled eye movement information 32 times per second. Results were compared to previous data collected on airline pilots flying standard approaches with standard instruments.

Results indicated altered scan patterns using the new displays when pilots flew curved and traditional approaches. During curved approaches, pilots spent 80 percent of their time scanning the EADI and the electronic horizontal situation indicator (EHSI) and made much fewer cross checks on conventional instruments. During straight approaches the dwell times on the new instruments did not increase over those that they replaced. Harris and Mixon (1981) concluded that given new procedures, new displays will have to be very reliable because pilots spend less time cross-checking other sources of information such as conventional round needle/dial displays.

Another scanning study was completed by NASA at Langly Field, Virginia, using the B-737 simulator equipped with the EADI. Waller, Harris, and Person (1982) used the same oculometer as had been employed in the last several studies cited. An infrared light source was reflected from the eye. The relative position of corneal reflections and those that come from the retina

through the pupil were used to compute look point or point of gaze. Visual data were recorded along with flight performance indicators such as control inputs and variances of aircraft altitude and rates of response (i.e., turn rate).

This was a very small sample study involving only seven test pilots. The oculometric data could not only identify what instrument pilots were using, but also what portion of it they were scanning. Results indicated that two of the seven pilots spent relatively less time using the "gamma wedges" and relatively more time on altitude information. Their Dwell percentages were 28 and 25 percent, respectively, while the other five pilots ranged from 47 to 56 percent scanning the wedges. There were performance differences between the two subgroups. The group that used the wedges during half their scan time, introduced significantly more longitudinal oscillations than did those who paid more attention to altitude. Using the oculometric data led Waller et al. (1982) to conclude that when you allow an operator a choice of information sources you may induce an incompatibility between display and control systems. Using the wedges meant that pilots had selected flightpath angle as their principle source of information. This data precedes aircraft pitch angle and led to increased pilot induced oscillations or PIOs.

The final cockpit study described here was completed by Tole, Stephans, Vivaudou, Harris, and Ephrath (1982). These researchers were looking for relationships between "mental loading" and visual scan paths of pilots. They believed that changes in scan pattern might be a workload indicator. Their study employed a desk top flight simulator and a Honeywell oculometer system. The sampling rate of the oculometer was stated as about 30 times per second. Mental loading on pilots was varied using a secondary task requiring them to generate a series of three number sequences based on a "math algorithm."

As mental loading was increased, there was an increase in Dwell times, especially on primary instruments. Skilled pilots were not as prone to this as novices whose scan patterns broke down as the load increased. Tole et al. (1982) concluded that less experience and more extraneous load coexisted with increases in entropy. Scan patterns became less organized and more chaotic--not a desirable situation for a complex person-machine system.

The applied cockpit studies of pilot eye movements are relevant to this current monograph in a number of ways. They are obviously concerned with aviation, and they involve human operators who need current information in dynamic person machine systems. The same could be said of ATC where the operators' interests expand from one--to the safety of many cockpits and the people in them.

AIR TRAFFIC CONTROL.

The relatively small amount of eye movement research that has been accomplished on radar controllers is surprising. Some of it was touched in the vigilance section of this paper; and, frankly, it was a judgement call as to whether it belonged there or here under applications. However, when one examines the frequency of projects, there has been little accomplished, and this is a fertile ground for research. What follows is a sampling of studies, which, to the best of our knowledge, exhausts the field of research in this area.

One of the older studies was completed by White and Ford (1960) who were concerned with operator search patterns. They had participants search for targets on a motion picture screen where they displayed 20 minutes worth of radar information photographed from a planned position indicator (PPI), an old radar display. They employed EOG and participants were required to position their heads using a dental impression bite board. Needless to say, real time participant verbal commands were not collected. The EOG was fed into an oscilloscope and time-lapse photographed. This provided an image of the final scan pattern. Results indicated a circular pattern which appeared to be driven by the radar scan line. This was very different from what would have occurred in free search and appears to have been a function of the display characteristics. The authors concluded that a circular display with a scan line constrains the search for targets.

Wallis and Samuel (1961) studied British Military Airborne Radar operators who monitored their displays for 3-hour periods. This was a small sample exploratory study using electrooculography provided by a system called the eye movement measurement apparatus, also referred to as an EMMA. This system measured the electrical potential changes between the front and rear of the eyeball, and plotted eye movements on an oscilloscope which could then be photographed. The authors did not clearly describe their results. They commented that there were individual differences between operators and that patterns of visual scanning may incorporate biases which can lead to inconsistent performance. Their major purpose was in the methodology rather than in generating definitive data.

Karston, Goldberg, Rood, and Sultzer (1975) evaluated the potential usefulness of a modified Honeywell oculometer to record the visual behavior of air traffic controllers. This exploratory work was done at the FAA Technical Center in Atlantic City, New Jersey. The oculometer system involved a helmet-mounted camera and infrared reflections from the controllers eyes. The camera directly recorded where the controller was looking and point of gaze was superimposed on the record of the visual scene. In their study the investigators asked how a controller divided his visual attention between the radar display, data entry devices,

flight strips, and miscellaneous areas. Six controllers worked three different 15-minute traffic scenarios.

Karston et al. (1975) described an initial problem with the oculometer. Sweeping eye movements could result in loss of tracking, a common problem in this type of system. Another problem was the restricted visual field due to the shape of the helmet. This forced head movements which also resulted in loss of tracking. When the system lost the participant's eyes, they had to be manually reacquired by an operator, which meant loss of data samples. Data reduction involved a manual procedure where the investigator watched the video tapes and made tallies on a synchronized kymograph recorder. This was a very coarse gained approach. Additional problems included operator eye dominance and pupil size. Light sensitive individuals may have constricted pupils less than 3 millimeters in diameter. This can confuse the discriminators between the pupil and the sclera reflections from the eyes surface of the cornea.

Despite these problems, the investigators felt the results were valuable. Controllers spent 80 percent of their time searching the radar, 11 percent on the flight strips, 5 percent on input devices and 3 percent on miscellaneous and undetermined. The researchers compared their oculometric data with results from over the shoulder observation. The oculometer data yielded a higher number of glances at specific sources and fewer undetermined glances. Participants found the helmet system only marginally acceptable; it weighed 4 pounds and restricted their vision. There is no published evidence that this system was ever used again at the FAA Technical Center. This could have been a function of its shortcomings or of changes in program orientation/emphasis.

Thackray and Touchstone (1980) at the Civil Aeromedical Institute have continued to be among the more prolific researchers and writers in the area of controller eye movements. Some of their work was cited earlier. In 1980, they revisited the question of the impact of the radar sweepline on visual search performance. They were also interested in the frequency of eye fixations and their relationship to performance. Twenty-eight non-controller university students monitored a simulated radar display for a 2-hour watch period, with and without a visible sweep line. They were instructed to press a button when they detected a change in the altitude portion of any aircraft's data block. Electrooculography was used to record horizontal saccades only because eye blinks confounded vertical recording. Results indicated no response latency differences between sweep and no sweep conditions. Mean eye fixation times declined between the first and the second 30 minutes of the monitoring period, then increased to their former level. There were no differences between sweep and no sweep and no evidence that eye movements were sweep driven. There were no significant relationships between response latencies and eye movements and performance.

In other tasks the general pattern of eye movements during prolonged monitoring has shown some systematic change involving a decline in the frequency of fixations. Logic dictates that as fixation frequency increases, the operator would access to more information. Why then was there no relationship between performance and eye movement data. One might speculate on the impact of the EOG measurement reliability and, perhaps, on the motivation and ability of non-controller university students.

The final applied work to be described here was done by David (1985) who examined the impact of color in tabular and radar displays. The researcher compared controller eye movement data for monochrome and color flight data and radar displays. Eye movements were recorded in three different ways: (1) over the shoulder observers using a digital timer, (2) video recording which had to be manually analyzed later, and (3) using an oculometer. The latter system must have been of European design; David published his work as a eurocontrol report. The equipment was referred to as a NAC Eye Mark Recorder Mark 5. The controller wears a helmet containing three video cameras. One records the direction of the head from a reference point; the other two can be used to record eye position and pupillary response. The author noted that his oculometer "is extremely intrusive and puts considerable constraints on the controller." At the time of the study, they were manually analyzing the taped results from the system. For technical reasons, eye mark data could only be taken on 22 minutes of each 90-minute simulated control session. Equipment setup and calibration took skill and time. Apparently, there was a steep learning curve on the use of this equipment.

The data were reduced to three variables: (1) percent of time looking at a display, (2) the number of glances per minute, and (3) the mean length of lances. The results on the impact of color were inconclusive. The mean differences across color and monochromatic displays were not significant. The study did confirm that radar controllers spend most of their time looking at the radar, which was no great surprise. A comparison of recording methods was useful. The direct observation and video techniques correlated fairly well. However, where eye mark oculometer recordings were available, the other two methods detected only 75 percent of the total glances and added about 15 percent false positives. The eye mark system could pickup on very short glances at a display, as little as 50 milliseconds which would be missed by an observer. In terms of intrusion, the video recording was least intrusive while the oculometer was the most bothersome and required constant adjustment.

This concludes the summary of the literature available and acquired. Eye movements are essential for the acquisition of visual information. While research on eye movements has occurred for many years, precious little has been done in ATC. This presents both a challenge and an opportunity. We anticipate fantastic gains from automation which controllers are expected to monitor. Yet, we currently know relatively little about how they go about scanning for information, given today's technology, so how can we reasonably design information displays for tomorrow?

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